CTP-TAMU-54/93
ACT-21/93

$b \to s\gamma$ and $Z \to b\bar{b}$ Constraints on Two Higgs Doublet Model

GYE T. PARK

Center for Theoretical Physics, Department of Physics, Texas A&M University
College Station, TX 77843–4242, USA
and
Astroparticle Physics Group, Houston Advanced Research Center (HARC)
The Woodlands, TX 77381, USA

ABSTRACT

We perform a combined analysis of two stringent constraints on two Higgs doublet model, coming from the recently announced CLEO II bound on $B(b \to s\gamma)$ and from the recent LEP data on the ratio $\frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)}$. We include one-loop vertex corrections to $Z \to b\bar{b}$ in the model. We find that although the CLEO II bound serves as the strongest constraint present in the charged Higgs sector of the model, the current LEP value for R_b may also provide a further constraint for $\tan\beta < 1$.

CTP-TAMU-54/93
ACT-21/93
August 1993

Despite the remarkable successes of the Standard Model(SM) in its complete agreement with current all experimental data, there is still no experimental information on the nature of its Higgs sector. The 2 Higgs doublet model(2HDM) is one of the mildest extensions of the SM, which has been consistent with experimental data. In the 2HDM to be considered here, the Higgs sector consists of 2 doublets, ϕ_1 and ϕ_2, coupled to the charge -1/3 and +2/3 quarks, respectively, which will ensure the absence of Flavor-Changing Yukawa couplings at the tree level [1]. The physical Higgs spectrum of the model includes two CP-even neutral Higgs(H^0, h^0), one CP-odd neutral Higgs(A^0) , and a pair of charged Higgs($H^{\pm}$). In addition to the masses of these Higgs, there is another free parameter in the model, which is $\tan\beta \equiv v_2/v_1$, the ratio of the vacuum expectation values of both doublets.

With a revived interest on the flavor-changing-neutral-current (FCNC) $b \to s\gamma$ decay, spurred by the CLEO bound $B(b \to s\gamma) < 8.4 \times 10^{-4}$ at 90% C.L. [3], it was pointed out recently that the CLEO bound can be violated due to the charged Higgs contribution in the 2HDM and the Minimal Supersymmetric Standard Model(MSSM) basically if $m_{H^\pm}$ is too light, excluding large portion of the charged Higgs parameter space [4]. The recently announced CLEO II bound $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95%[5] excludes even larger portion of the parameter space [6]. It has certainly proven that this particular decay mode can provide more stringent constraint on new physics beyond SM than any other experiments[7]. In this report, we will show that in addition to the CLEO II bound on $b \to s\gamma$, one may be able to constrain the 2HDM further, by incorporating one-loop vertex corrections to $Z \to b\bar{b}$, with the recent LEP data on R_b[8], which is defined to be the ratio $\frac{\Gamma(Z\to b\bar{b})}{\Gamma(Z\to hadrons)}$. A number of authors in fact have studied the one-loop corrections to $\Gamma(Z \to b\bar{b})$ in the context of the SM[9] and a few extensions of it [10, 11, 12] although the emphases were different.

In the 2HDM, $b \to s\gamma$ decay receives contributions from penguin diagrams with $W^{\pm} - t$ loop and $H^{\pm} - t$ loop. The expression used for $B(b \to s\gamma)$ is given by [13]

$$\frac{B(b \to s\gamma)}{B(b \to ce\bar{\nu})} = \frac{6\alpha}{\pi} \frac{\left[\eta^{16/23}A_\gamma + \frac{8}{3}(\eta^{14/23} - \eta^{16/23})A_g + C\right]^2}{I(m_c/m_b)\left[1 - \frac{2}{3\pi}\alpha_s(m_b)f(m_c/m_b)\right]}, \tag{1}$$

where $\eta = \alpha_s(M_Z)/\alpha_s(m_b)$, I is the phase-space factor $I(x) = 1 - 8x^2 + 8x^6 - x^8 - 24x^4 \ln x$, and $f(m_c/m_b) = 2.41$ the QCD correction factor for the semileptonic decay. We use the 3-loop expressions for α_s and choose Λ_{QCD} to obtain $\alpha_s(M_Z)$ consistent with the recent measurements at LEP. In our computations we have used: $\alpha_s(M_Z) = 0.118$, $B(b \to ce\bar{\nu}) = 10.7\%$, $m_b = 4.8\,\mathrm{GeV}$, and $m_c/m_b = 0.3$. The A_γ, A_g are the coefficients of the effective $bs\gamma$ and bsg penguin operators evaluated at the scale M_Z. The contributions to $A_{\gamma,g}$ from the $W^\pm - t$ loop, the $H^\pm - t$ loop are given in Ref[13]. As mentioned above, the CLEO II bound excludes a large portion of the parameter space. In Fig. 1 we present the excluded regions in ($m_{H^\pm}$, $\tan\beta$)-plane for $m_t = 120, 130,$ and $150\,\mathrm{GeV}$, which lie to the left of each curve. We have imposed in the figure also the lower bound on $\tan\beta$ from $\frac{m_t}{600} \lesssim \tan\beta \lesssim \frac{600}{m_b}$ obtained by demanding that the theory remain perturbative[14]. We see from the figure that at

large $\tan\beta$ one can obtain a lower bound on $m_{H^\pm}$ for each value of m_t. And we obtain the bounds , $m_{H^\pm} \gtrsim 160, 186, 244\,\mathrm{GeV}$ for $m_t = 120, 130, 150\,\mathrm{GeV}$, respectively. Our strategy is now to sample $\tan\beta$ and $m_{H^\pm}$ from the allowed regions in Fig. 1, which will be in turn used below to calculate R_b at one-loop level in this model.

In the SM, the diagrams for the vertex corrections to $Z \to b\overline{b}$ involve top quarks and $W^\pm$ bosons. However, in the 2HDM there are additional diagrams involving $H^\pm$ bosons instead of $W^\pm$ bosons. These additional diagrams have been calculated in Ref[10, 11, 12]. Here we use the formulas given in Ref[11]. The calculation involves numerical evaluation of the reduced Passarino-Veltman functions[15]. Our numerical results agree with those in Fig. 4-5 in Ref[11]. In our calculation, we neglect the neutral Higgs contributions which are all proportional to $m_b^2 \tan\beta^2$ and become sizable only for $\tan\beta > \frac{m_t}{m_b}$ and very light neutral Higgs $\lesssim 50\,\mathrm{GeV}$, but decreases rapidly to get negligibly small as the Higgs masses become $\gtrsim 100\,\mathrm{GeV}$[12]. We also neglect oblique corrections from the Higgs bosons just to avoid introducing more paramters. This correction grows as $m_{H^\pm}^2$ if $m_{H^\pm} \gg m_{H^0,h^0,A^0}$, and gives only a -0.1% correction for $m_{H^\pm} = 500\,\mathrm{GeV}$. Although $\tan\beta \gg 1$ seems more appealing because of apparent hierarchy $m_t \gg m_b$, there are still no convincing arguments against $\tan\beta < 1$. Here we choose to explore the region of $\tan\beta \lesssim 1$. In Fig. 2 we show the model predictions for R_b as a function of m_t in comparison with the SM prediction. The parameters were sampled from the allowed regions in the Fig. 1. Two horizontal solid lines in the figure represent the lower limits from the recent LEP data $R_b = 0.2203 \pm 0.0027$[8]. The upper one corresponds to the 1-σ value, and the lower one to the 1.64-σ value. We note that the deviations from the SM can be quite large for $\tan\beta < 1$ because the charged Higgs contribution grows as $m_t^2/\tan^2\beta$ for $\tan\beta \ll \frac{m_t}{m_b}$. The deviations for $\tan\beta < 1$ can be as large as -2.2% for $m_t = 150\,\mathrm{GeV}$ while they become much smaller for $\tan\beta > 1$[16]. We have also considered other constraints from low-energy data primarily in $B-\overline{B}, D-\overline{D}, K-\overline{K}$ mixing that exclude low values of $\tan\beta$[14, 17]. But $\tan\beta \lesssim 0.5$ seems to be still allowed by these constraints for $m_t \lesssim 150\,\mathrm{GeV}$ and $m_{H^\pm} \gtrsim 250\,\mathrm{GeV}$. However, for small values of $\tan\beta$, as is seen from Fig. 2, the model predicts $m_t \lesssim 110\,\mathrm{GeV}$ at 1-σ level, which is in conflict with the recent bound from CDF[18], $m_t > 113\,\mathrm{GeV}$ although the corresponding prediction at 1.64-σ level is still allowed . These low values of $\tan\beta \lesssim 0.5$ might be at the verge of being disfavored even at 90%C.L. as the experimental lower bound on m_t tends to grow. Nevertheless, the CLEO II bound is still by far the strongest constraint present in the charged Higgs sector of the model especially for $\tan\beta \gtrsim 1$.

In the MSSM, the situation becomes much more complicated. In the calculation of $B(b \to s\gamma)$ in Ref[4], other important contributions such as chargino-squark contribution were not included. However, it was shown very recently[13] that the bound on $m_{H^\pm}$ in Ref [4] could well be evaded in the full supersymmetric calculation since the $b \to s\gamma$ amplitude vanishes in the exact supersymmetric limit. Therefore, with full calculations, one may get significantly smaller bounds on $m_{H^\pm}$ than the ones given above[7]. However, adding supersymmetric particles raises R_b significantly above the SM value due to chargino-squark loops and neutralino-squark loops can-

celling out to a great extent the charged Higgs constribution and also the standard contribution[11]. Thus, this makes it extremely difficult for one to be able to constrain the MSSM with the current LEP data.

In conclusion, we have performed a combined analysis of two stringent constraints on the 2 Higgs doublet model, coming from the recently announced CLEO II bound on $B(b \to s\gamma)$ and from the recent LEP data on R_b. We have included one-loop vertex corrections to $Z \to b\bar{b}$ in the model. We find that although the CLEO II bound serves as the strongest constraint present in the charged Higgs sector of the model, the current LEP value for R_b may also provide a further constraint for $\tan\beta < 1$.

Acknowledgements

The author thanks the Center for Theoretical Physics at Seoul National University for their hospitality during early stage of this work. This work has been supported by the World Laboratory.

References

[1] S. Glashow and S. Weinberg, Phys. Rev. D **15** (1977) 1958.

[2] S. Bertolini, F. Borzumati, A. Masiero, and G. Ridolfi, Nucl. Phys. B **353** (1991) 591.

[3] M. Battle *et. al.* (CLEO Collab.) in Proceedings of the joint Lepton-Photon and Europhysics Conference on High-Energy Physics, Geneva 1991.

[4] J. Hewett, Phys. Rev. Lett. **70** (1993) 1045; V. Barger, M. Berger, and R. J. N. Phillips, Phys. Rev. Lett. **70** (1993) 1368.

[5] E. Thorndike, talk given at the 1993 Meeting of the American Physical Society, Washington D. C., April 1993; R. Ammar *et. al.* (CLEO Collab.), Phys. Rev. Lett. **71** (1993) 674.

[6] V. Barger and R. J. N. Phillips, to appear in the Proceedings of the HARC workshop "Recent Advances in the Superworld", The Woodlands, Texas, April 1993.

[7] J. L. Lopez, D. V. Nanopoulos, and G. T. Park, Phys. Rev. D **48** (1993) R974; G. T. Park, to appear in the Proceedings of the HARC workshop "Recent Advances in the Superworld", The Woodlands, Texas, April 1993; J. L. Lopez, D. V. Nanopoulos, G. T. Park, and A. Zichichi, Texas A & M University preprint CTP-TAMU-40/93.

[8] W. Venus, A talk given at the Lepton-Photon Conference, Cornell University, Ithaca, New York, August 1993. The author thanks Prof. T. K. Kuo for making available the reported value for R_b.

[9] J. Bernabeu, A. Pich, and A. Santamaria, Phys. Lett. B **200** (1988) 569; W. Beenaker and W. Hollik, Z. Phys. C40, 141(1988); A. Akhundov, D. Bardin, and T. Riemann, Nucl. Phys. B **276** (1986) 1; F. Boudjema, A. Djoiadi, and C. Verzegnassi, Phys. Lett. B **238** (1990) 423.

[10] A. Djoiadi, G. Girardi, C. Verzegnassi, W. Hollik, and F. Renard, Nucl. Phys. B **349** (1991) 48.

[11] M. Boulware and D. Finnell, Phys. Rev. D **44** (1991) 2054.

[12] A. Denner, R. Guth, W. Hollik, and J. Kühn, Z. Phys. C51, 695(1991).

[13] R. Barbieri and G. Giudice, Phys. Lett. B **309** (1993) 86.

[14] V. Barger, J. Hewett, and R. J. N. Phillips, Phys. Rev. D **41** (1990) 3421.

[15] C. Ahn, B. Lynn, M. Peskin, and S. Selipsky, Nucl. Phys. B **309** (1988) 221.

[16] For $\tan\beta > \frac{m_t}{m_b}$, the charged Higgs contribution can also become sizable due to its large $\tan\beta$ dependence of $m_b^2 \tan^2\beta$. For example, it yields a -0.25% deviation for $\tan\beta = 70$, $m_{H^\pm} = 250\,\mathrm{GeV}$, and $m_t = 150\,\mathrm{GeV}$. For large $\tan\beta$, see Ref[12].

[17] A. Buras et al., Nucl. Phys. B **337** (1990) 284.

[18] P. Tipton, CDF Collaboration, a talk given at the Lepton-Photon Conference, Cornell University, Ithaca, New York, August 1993.

Figure Captions

Figure 1: The regions in $(m_{H^\pm}, \tan\beta)$ plane excluded by the CLEO II bound $B(b \to s\gamma) < 5.4 \times 10^{-4}$ at 95%, for $m_t = 120, 130, 150\,\mathrm{GeV}$ in 2HDM. The excluded regions lie to the left of each curve. The values of m_t used are as indicated.

Figure 2: R_b as a function of top mass in the SM(Solid), and the 2HDM for five different sets of $\tan\beta$ and $m_{H^\pm}$ sampled from the allowed regions in the Fig. 1. The values of $(\tan\beta,\ m_{H^\pm})$ used are as indicated under each curve. Two horizontal solid lines represent the lower limits from the recent LEP data $R_b = 0.2203 \pm 0.0027$. The upper one corresponds to the 1-σ value, and the lower one to the 1.64-σ value. Anything above these lines is allowed.